Journal of Hydrology 511 (2014) 800–810

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Impact of plant growth and morphology and of sediment concentration on sediment retention efficiency of vegetative filter strips: Flume experiments and VFSMOD modeling

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ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form 1 December 2013
Accepted 10 February 2014
Available online 22 February 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ehab A. Meselhe, Associate Editor

Keywords:
Water erosion
Vegetative filter strips
Plant growth
Particle size distribution
Sediment concentration
VFSMOD

SUMMARY

Vegetative filter strips (VFS) implemented downstream to the source of pollution can trap sediments and thus limit sediment export from agricultural fields. However, their retention efficiencies are determined by many factors, among others the type of plant species and its growth stage. The impact of plant growth and morphology, as well as of incoming sediment concentration, on the efficiency of VFS to trap sediments was assessed by means of an experimental flume. Two different plant species were tested, *Lolium perenne* and *Trifolium repens*, after 2 and 4 months of plant growth and for 2 different incoming silty-loam sediment concentrations. Measured retention efficiencies were compared to simulated values using VFSMOD based on goodness-of-fit indicators that take into account uncertainty linked to the measurements.

The sediment storage capacity upstream of the VFS was limited in terms of mass, and therefore an increase in sediment concentration led to a decrease in sediment retention efficiency. After 2 months of plant growth, plant morphology affected the VFS potential to trap sediments, as reflected in the higher retention efficiency of *T. repens* due to its creeping shoot architecture. However, plant growth and development modified the plant morphology and VFS trapping potential. Indeed, *L. perenne* VFS retention efficiency increased from 35% after 2 months of growth to 50% after 4 months, due to the tillering capacity of grass species. Conversely, the trapping efficiency of *T. repens* decreased from 49% to 40% after 4 months. This highlights the possible degradation of VFS with time, which in the case of *T. repens* was due to an increased heterogeneity of plant density within the strips. These modifications of plant characteristics with growth stage, which affected sediment trapping efficiencies, can be effectively integrated into mechanistic models like VFSMOD, mainly through stem spacing and Manning's surface roughness coefficient inputs. Since these parameters were highly conditioned by plant growth and development, modelers should take into account plant dynamics and select plant parameters related to the actual field conditions.

1. Introduction

Vegetative filter strips (VFS) are bands of planted or indigenous vegetation situated downslope of the source of sediment or pollution to provide localized erosion protection and filter sediments from runoff (Dillaha et al., 1989). VFS act on erosion through several mechanisms (Blanco and Lal, 2008; Krutz et al., 2005; Muñoz-Carpena et al., 1999). The increased hydraulic roughness caused by the vegetation and plant debris results in the slowing down of runoff. Plant roots increase the resistance of soils to erosion (Gyssels et al., 2005; Reubens et al., 2007) and may improve the soil permeability, thus decreasing the runoff amount by infiltration as long as the precipitation rate does not exceed the infiltration capacity of the VFS. Reductions in flow velocity and volume jointly decrease the sediment transport capacity of the runoff, thus promoting sedimentation upstream of the VFS as well as within the VFS.

VFS are established best management practices in Europe and the USA to control soil erosion and sediment and agrichemical exports from agricultural fields (Dorioz et al., 2006; USDA, 2000). Many authors have shown the effectiveness of VFS to trap sedi-

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http://dx.doi.org/10.1016/j.jhydrol.2014.02.030
0022-1694/© 2014 Published by Elsevier B.V.

ments. Dorioz et al. (2006) performed a critical review of all the experiments on this topic, and showed that sediment retention ranged from 40% to 100%, with more than 50% reduction in more than 95% of the cases. Dunn et al. (2011) monitored VFS effectiveness in operational farms in Prince Edward Island (Canada) and demonstrated that results under field conditions matched with controlled experiments.

The effectiveness of sediment retention is complex to predict, depending not only on the rainfall and runoff characteristics (rainfall intensity, inflow discharge and velocity, slope, sediment concentration), the VFS area to source area ratio and on the soil and sediment properties (particle size, infiltration, roughness), but also on the vegetation characteristics (width, plant species and density, plant height) as well as on VFS installation and management (Blanco and Lal, 2008; Liu et al., 2008; Muñoz-Carpena et al., 2010; Reichenberger et al., 2007). Some authors focused specifically on the effect of plant parameters. For a given species, it is well-known that an increase in plant cover and density improves sediment retention (Morgan, 2005). However, it is more complicated to quantify the impact of the plant morphology and growth on the trapping efficiency. Fasching and Bauder (2001) tested eight species and showed that plants which produced the greatest amount of shoot biomass in the shortest period of time also produced the greatest basal area and reduced erosion the most. Other studies focused on shoot architecture parameters such as tillering, shoot posture or stem diameter, and demonstrated the impact of shoot architecture on sediment filtration, which acts as a more or less efficient barrier against runoff (Krutz et al., 2005; Melville and Morgan, 2001; Xiao et al., 2011). Therefore, there is a need to better understand the impact of plant morphology for plant species adapted to local environmental conditions. Moreover, differences in plant growth dynamics should be taken into consideration as they impact the efficiency of VFS during the first months after installing the VFS (Dorioz et al., 2006).

Several dedicated models have been developed regarding sediment retention by VFS, such as GRASSF (Hayes et al., 1984), TRAVA (Deletic, 2005) or VFSMOD (Muñoz-Carpena et al., 1999). The Vegetative Filter Strip Modeling System (VFSMOD-W) is a field-scale, mechanistic, event-based numerical model developed to route the incoming hydrograph, sediment and water pollutants from an adjacent field through a VFS and to calculate the resulting outflow, infiltration as well as sediment and pesticide trapping efficiency (Muñoz-Carpena et al., 1999, 2010; Muñoz-Carpena and Parsons, 2004, 2011). Good agreement between observed sediment retention under field conditions and VFSMOD modeling results has been obtained in several studies (Abu-Zreig, 2001; Han et al., 2005; Muñoz-Carpena et al., 1999; Poletika et al., 2009). In conjunction with other tools, the model could be used as a support tool for placement and design of VFS in the field (Dosskey et al., 2006, 2011; White and Arnold, 2009). The impact of plants can be integrated into VFSMOD through several parameters: Manning's roughness coefficient of the VFS (measured in the field or taken from the literature) for the overland flow module of VFSMOD; and the microscale modified Manning's roughness coefficient for cylindrical media, calculated for different plant species (Haan et al., 1994), grass spacing and grass height for the sediment filtration module. Although these parameters change according to plant growth and development, as well as seasons, their variation is not systematically taken into account by modelers.

The main objective of this study was to analyze the impact of plant characteristics on sediment trapping efficiency, taking into account plant growth dynamics, for different incoming sediment concentrations. Both total efficiency and the retention efficiency of the different particle size classes were investigated. An experimental flume was used to assess the sediment retention efficiency of VFS composed of *Lolium perenne* or *Trifolium repens* at different growth stages (2 and 4 months after germination). The experimental results were compared to simulation results from VFSMOD in order to test whether the model could take into account the changes in plant characteristics with growth stage. The use of VFSMOD also helped describe the sediment retention mechanisms by VFS.

2. Materials and methods

2.1. Experimental flume

The experimental flume (Fig. 1) was designed to test the effectiveness of VFS to trap sediments, with the possibility to modify several experimental conditions (slope, runoff discharge, sediment concentration, plant parameters). The device consisted in an inclined board (length: 2 m; width: 1.16 m) coated with small gravel (1–3 mm) with adjustable slope. Runoff (water and a mix of water and sediment) was introduced through 2 inputs at the top of the flume. No water was applied as rainfall. A system of pumps and tubes delivered runoff with a given sediment concentration (coefficient of variation of sediment flow across the board width: 24%).

VFS could be inserted into the experimental flume. They consisted of an iron grid (1 m × 0.55 m × 0.05 m) covered with a mosquito net and filled with air-dried, crushed and non-stony silty-loam soil sampled from an agricultural field. For the present experiment, the VFS rested on an impervious substrate, i.e., free drainage was not allowed.

At the outlet of the VFS, water discharge could be measured by means of previously calibrated tipping buckets, and a splitter device (Giboire et al., 2003) allowed collecting a fraction of the runoff for determination of sediment concentration and measurement of sediment physico-chemical characteristics. A detailed description of this experimental flume was reported in Lambrechts (2013).

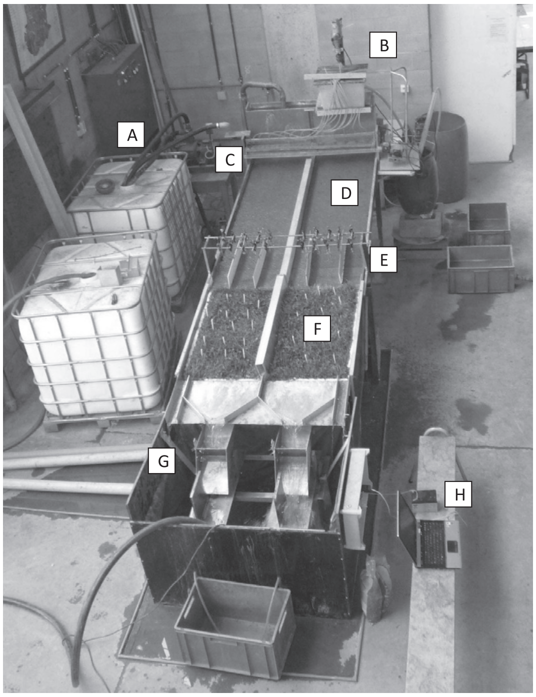

Fig. 1. Experimental flume used to assess the retention efficiency of vegetative filter strips. A: input 1, water tanks + pump; B: input 2, sediment tank + mixers + pump; C: mix and dispersion of inputs; D: inclined rough board with variable slope; E: measurement of water depth; F: vegetative filter strips; G: Measurement of the water discharge and the sediment concentration, tipping bucket with splitter device; H: datalogger.

2.2. Experimental design

The soil used for sediment input was sampled from a silty-loam agricultural field. Soil was collected from the first 20 cm, air-dried, mixed and sieved through a 2-mm mesh before use. Five samples were randomly collected from this bulk sample for the determination of particle size distribution by sieving (>50 μm) and by the hydrometer method (<50 μm), after dispersion of the clay and silt fraction by sodium hexametaphosphate (Gee and Bauder, 1986).

Two different kinds of VFS were used: *L. perenne* cv. Mondial, *T. repens* cv. Alice. Bare soil was used as a control. Plants were sown at a density of 45 kg ha^{-1} and left to grow for 2 and 4 months after germination under greenhouse conditions. The 2-month and 4-month experiments were performed with different VFS for the same plant species. Plants were mown before the experiment at 7.5 cm height to avoid lodging. The 5 different experimental treatments (2 species × 2 growth durations + control) were tested for 2 sediment concentrations (38.8 ± 0.8 g l^{-1}, 23.4 ± 0.3 g l^{-1}; mean ± SD), with 4 replicates per treatment. Each run lasted about 15 min. For all runs, a slope of 8% and unit discharge of 1.46 ± 0.02 m^2 h^{-1} were selected to represent the steady state discharge of a 100 m long slope subjected to a constant rainfall intensity of 100 mm h^{-1} and having a runoff coefficient (runoff volume/rainfall volume) of 15%. Such an event has a 20-year return period under the field conditions of central Belgium (Evrard et al., 2009; Steegen et al., 2000).

Thin PVC plates coated with brilliant blue dye were inserted vertically length-wise upstream of the VFS in order to monitor the water depth of the runoff discharge, by measuring the height of the strip where water had washed away the dye. Different sets were used to monitor water depth at different times during a run. Fifteen coated rods were also inserted into the VFS for the determination of water depth inside the strips. These measurements were used among others for calculation of Manning's roughness coefficient.

For each experiment, the following measurements were performed. Three times during each run, volumes of 100 ± 2 ml were sampled at mid-height in the incoming-sediment tank. Oven dry weights were determined after 72 h at 105 °C. From these values, incoming sediment concentrations and total mass were calculated. Volumes of 100 ± 2 ml were sampled every two minutes at the outlet of the flume with the splitter device for the determination of outgoing sediment concentrations and masses. Sediment deposits upstream of the filter strips were also quantified. The height of sediment deposits upstream of the VFS was measured with an electronic caliper along a 5-cm grid. Mean bulk density was determined by collecting a given volume of deposited sediment and measuring the dry weight three times for each run. At the end of the experiment, all the potential artefacts, i.e., sediment deposits in the different tanks of the flume, were also quantified. Artefacts were taken into account by subtracting from the incoming mass all the potential sediment deposits in the tanks up to the VFS. Sediment retention (kg) in the strips was calculated by subtracting from the corrected incoming mass the outgoing mass and the mass of sediment deposited upstream of the VFS. Total sediment retention corresponds to the sediment retained in the strips and upstream of the VFS. Retention efficiency is the ratio (%) between the trapped mass and the corrected incoming mass.

For each run and location in the flume (incoming, outgoing, upstream of the VFS and artefacts), the different dried samples were pooled and homogenized. Soil particle size distribution was assessed by sieving and sedimentation as explained above. Plant density for each filter strip was estimated after the experiment. The number of stems per unit area was determined three times per strip for random locations. The standard error was used as an indication of the level of heterogeneity of the VFS.

2.3. Statistical analysis

Sediment retention efficiencies for bare soil and VFS (whatever the plant species) were statistically compared with 1-way ANOVA (Student Newman–Keuls test). Sediment retention efficiencies, Manning's roughness coefficient for the strips and particle size distributions were subjected to statistical analyses using 3-way ANOVA (SAS System for Windows, version 9.2) assuming a randomized experiment with 3 factors (plant species, growth duration and incoming sediment concentration) of 2 levels each and 4 replicates per treatment. A post-ANOVA "simple effects" analysis was performed to explore the nature of the significant interaction between plant species and growth duration. Stem spacing data were subjected to 2-way ANOVA considering 2 factors (plant species and growth duration). Statistical significance was assessed at the 5% level, with a Welch correction when there was no equality of the variance (Levene's test). Pearson correlation coefficients were determined between different variables at the 5% level.

2.4. Derivation of input parameters for VFSMOD simulations

All the input parameters required for the model were derived from experimental data (Table 1; Figs. 2–4). Concerning the parameters for the resolution of the infiltration module, rainfall intensity during all the simulations was set to zero. VFS were saturated with water before the experiments and no infiltration was allowed below the strips, so the soil saturated hydraulic conductivity was set to 0.

Regarding the parameters for the numerical resolution of the overland flow equation, default values recommended by the authors of the model were selected (Muñoz-Carpena and Parsons, 2011), except for the ones specified in Table 1. Runoff unit dis-

Table 1
Hydrological and sediment transport input parameters used for VFSMOD.

Parameters	Values	Units
Infiltration module		
Rainfall intensity	0	m s^{-1}
Saturated hydraulic conductivity	0	m s^{-1}
Initial soil–water content	0.311	m^3 m^{-3}
Saturated soil–water content	0.311	m^3 m^{-3}
Maximum surface storage	0	m
Overland flow module		
Strip width	0.55	m
Strip length	1	m
Number of strip segments	1	–
Strip Manning's roughness	Variable (Fig. 2)	–
Slope	0.08	m m^{-1}
Source area width	0.55	m
Source area flow path length	2	m
Time steps for incoming hydrograph	Variable for each experiment	–
Incoming hydrograph duration	Measured, variable for each experiment	s
Incoming hydrograph flow	Measured, variable for each experiment	m^3 s^{-1}
Sediment filtration module		
Vegetation spacing	Measured, variable (Fig. 3)	cm
Filter media Manning's	0.012 (Lolium); 0.016 (Trifolium)	–
Vegetation height	7.5	cm
Bare surface Manning's sediment	0.319	–
inflow concentration	Measured, variable for each experiment	g cm$^{-1/3}$
Coarse particles (d > 37 μm)	0.27 (Fig. 4)	Unit fraction
Sediment particle size (d_{50})	0.00275 (Fig. 4)	cm
Porosity of deposited sediment	0.434	unit fraction
Sediment particle density	2.65	g cm$^{-1/3}$

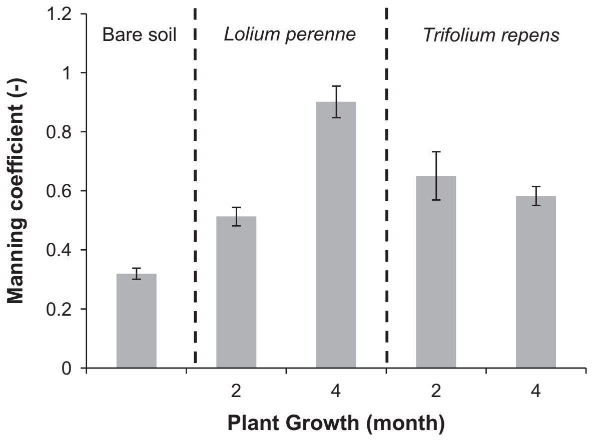

Fig. 2. Manning coefficient (s m$^{-1/3}$) of different vegetative filter strips (*Trifolium repens*, *Lolium perenne* and bare soil as control) measured 2 or 4 months after plant germination. Values are means ($n = 8$), standard errors as error bars.

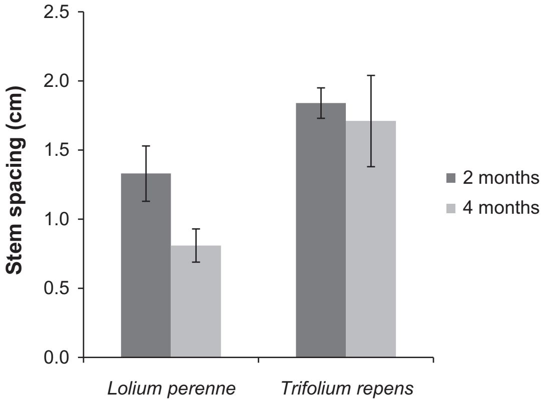

Fig. 3. Stem spacing (cm) of different vegetative filter strips (*Trifolium repens* and *Lolium perenne*) measured 2 or 4 months after plant germination. Values are means ($n = 8$), standard errors as error bars.

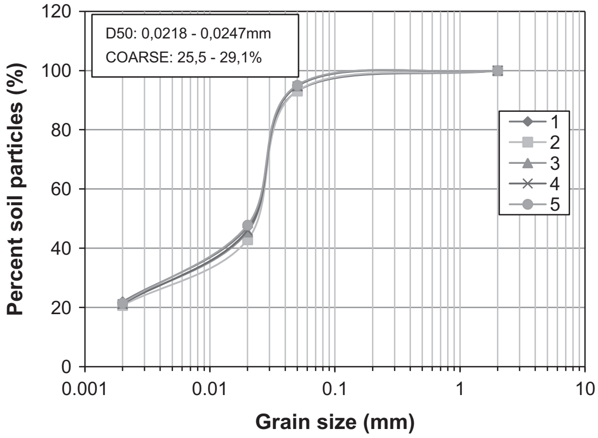

Fig. 4. Particle size distribution of the incoming sediments in runoff ($n = 5$) and indication of the range of variation for 2 VFSMOD parameters: d_{50} = median sediment particle size diameter (mm), coarse = percentage of soil particles with $d > 37$ µm (%).

charge (1.46 ± 0.02 m^2 h^{-1}, for a total water volume of 424 ± 9 l) was recorded by the tipping buckets in the experimental flume. Manning's coefficients for the strips (Fig. 2) were obtained through measurements of flow discharge and water height in the strips according to the empirical formula for open channel flow:

$$V = \frac{k}{n} R^{2/3} \sqrt{S} \tag{1}$$

where V is the flow velocity (m s^{-1}), k = 1 m$^{1/3}$ s^{-1} if all units are in SI units, n is Manning's hydraulic roughness coefficient (–), R is the hydraulic radius, approximated here by the flow height (m) measured by dye coated rods, and S is the flume slope (m m^{-1}).

Concerning the buffer strip properties for the sediment filtration model, vegetation spacing data (Fig. 3) were obtained by means of Eq. 2 (Muñoz-Carpena, 1993), where SS is the stem spacing (cm) and D_s the measured stem density (stem m^{-2}):

$$SS = \sqrt{\frac{1}{D_s} * 100} \tag{2}$$

Manning's coefficient for the bare soil was the mean of the Manning's coefficients for the eight strips without plant cover. The microscale modified Manning's roughness coefficient for cylindrical media was determined for *L. perenne* and *T. repens* based on Haan et al. (1994). For the incoming sediment properties, the percentage of particles with a diameter greater than 37 µm and the median sediment particle size were assessed from the measured sediment particle size distributions, assuming complete dispersion (Fig. 4).

2.5. Model application

Based on previous sensitivity analyses (Muñoz-Carpena et al., 2007, 2010; Fox et al., 2010), five sensitive input factors for the sediment filtration submodel (Table 1) were initially selected for model calibration. These factors encompassed sediment inputs (sediment inflow concentration, percentage of coarse particles and median sediment particle size) and buffer strip properties (stem spacing and microscale modified Manning's coefficient). However, in our experiment, the uncertainty on stem spacing measurements was lower than for sediment properties. Moreover, the microscale Manning's coefficient can only be assessed based on tabulated data (Haan et al., 1994). Therefore, calibration was performed on the three sediment variables for the sediment filtration module of VFSMOD for each run. A range of variation for each variable for the calibration process was selected, based on experimental measurements. For the percentage of coarse particles and mean particle size, these ranges were defined on the basis of Fig. 4. For sediment concentration, all the measurements of incoming sediment mass (3 replicates per test) were used to build frequency histograms for the two selected sediment concentration classes. After removal of outliers, minimum and maximum values of incoming masses were determined for each concentration treatment (low concentration: 15.33–20.92 kg; high concentration: 30.02–39.63 kg), in order to calculate minimum and maximum sediment inflow concentrations for each test.

The inverse modeling module integrated into VFSMOD was used to perform the calibration of the three selected parameters (Ritter et al., 2007; Kuo and Muñoz-Carpena, 2009). This calibration procedure minimizes the following objective function:

$$OF(\vec{b}) = \sum_{i=1}^{N} w_i \left[O(t_i) - P(t_i, \vec{b}) \right]^2 \tag{3}$$

where $OF(\vec{b})$ is the objective function value for parameter vector $\vec{b}$ that represents the error between measured and simulated values ; $O(t_i)$ are observed values at time t_i, and $P(t_i)$ are predicted values (sedimentographs) using parameter vector $\vec{b}$; N is the number of measurements available during a run and w_i is the weight of a particular measurement (Lambot et al., 2002). Here, equal weight was granted to each observation time. VFSMOD was coupled with the Global Multilevel Coordinate Search (GMCS) algorithm (Huyer and Neumaier, 1999) combined sequentially with the classical Nelder–Mead Simplex (NMS) algorithm (Nelder and Mead, 1965) (GMCS–NMS) to perform the inverse calibration of parameter vector $\vec{b}$ (Ritter et al., 2007).

In order to perform the calibration procedure for each run, observed sedimentographs at the outlet were calculated using measured discharge and sediment concentrations. As opposed to discharge, sediment concentrations at the outlet of the flume were not constant but increased regularly over time at an approximately constant rate, as the maximum trapping capacity of the strips was progressively reached (Pan et al., 2011). A linear regression was performed on the observed time series of sediment concentrations in runoff. The regression was then used to estimate sediment concentration, and hence the sedimentograph, with a time step of 30 s.

After calibration, simulated outflow volumes, outflow sediment masses and trapping efficiencies were compared with the corresponding experimental values through the use of scatterplots and calculation of the Nash and Sutcliffe coefficient of efficiency (C_{eff}) and root mean square error (RMSE).

Uncertainty arising from the determination of initial and boundaries conditions, from the measurements of parameters and from unobserved input disturbances of the system is inherent to many experiments (Beck, 1987; Beven, 2001). In our experiments, the uncertainty inherent to the measured incoming and outgoing sediment concentration data used for calibrating the model was included into the evaluation of model performance based on an adaptation of the method proposed by Harmel and Smith (2007). This kind of approach provides an opportunity to the modelers to deal in a simplified way with the crucial issue of uncertainty in model evaluation (Beven, 2006; Harmel and Smith, 2007; Reckhow, 1994). Minimum and maximum incoming sediment masses were derived from the frequency histograms previously determined for the incoming sediment masses. However, it is very difficult to quantify the uncertainty linked to the outgoing sediment masses. Therefore, uncertainty on outgoing sediment was not taken into account. The minimum [$M_{\text{inc}}(\text{min})$] and maximum [$M_{\text{inc}}(\text{max})$] values of incoming sediment masses were used to calculate minimum and maximum retention efficiencies for each experimental run, which were respectively the lower [$UO_i(l)$] and upper [$UO_i(u)$] uncertainty boundaries for the experimental retention efficiency O_i:

$$UO_i(l) = \frac{M_{\text{Inc}}(\text{min}) - M_{\text{out}}}{M_{\text{Inc}}(\text{min})} \tag{4}$$

$$UO_i(u) = \frac{M_{\text{Inc}}(\text{max}) - M_{\text{out}}}{M_{\text{Inc}}(\text{max})} \tag{5}$$

where M_{inc} is the incoming sediment mass and M_{out} the outgoing sediment mass. These uncertainty boundaries were added to the predicted vs. measured efficiency scatterplots. They were also used to calculate the modified deviation eu_i taking into account the uncertainty:

$$eu_i - 0 \text{ if } UO_i(l) \leqslant P_i \leqslant UO_i(u)$$

$$eu_i = UO_i(l) - P_i \text{ if } P_i < UO_i(l)$$

$$eu_i = UO_i(u) - P_i \text{ if } P_i > UO_i(u) \tag{6}$$

where P_i is the predicted retention efficiency. These modified deviations eu_i were used to calculate the modified C_{eff} and RMSE:

$$C_{\text{eff}} = 1 - \frac{\sum_{i=1}^{n} (eu_i)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2} \tag{7}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (eu_i)^2}{n}} \tag{8}$$

where $\overline{O}$ is the mean of observed data, n is the number of observed data. The software FITEVAL (Ritter and Muñoz-Carpena, 2013) was used in the calculation of the graphical and statistical goodness-of-fit indicators including uncertainty in the observed data.

3. Results

3.1. Experimental results

Sediment retention efficiencies upstream of the strips, in the strips and the total retention, as well as the sediment masses trapped, are given in Fig. 5. The majority of total sediment retention resulted from retention in the strips, and not by retention upstream of the strips. A significant impact of the presence of plants, irrespective of plant species, was detected in comparison to control strips for total retention (one-way ANOVA, Student–Newman–Keuls test). However, on average across all development stages and sediment concentrations, there was no significant effect of plant species on retention efficiency. Across all species and sediment concentrations, plant growth stage also had no significant impact on this output. However, a significant plant growth stage x plant species interaction existed ($p = 0.0032$). *T. repens* strips trapped significantly more sediment after 2 months than *L. perenne* strips, but the opposite was observed after 4 months of plant growth. Based on the simple effects analysis, total sediment retention significantly increased for *L. perenne* with growth duration ($p = 0.0033$), as opposed to *T. repens* for which retention showed a tendency to decrease after 4 months ($p = 0.0626$). Finally, although runoff sediment concentration had no impact on total sediment retention efficiency, sediment trapping efficiency upstream of the VFS was significantly affected by sediment concentration ($p = 0.0006$). Indeed, the sediment mass retained upstream to the VFS did not increase significantly when the incoming sediment mass increased (Fig. 6). Therefore, an increase in sediment concentration significantly decreased the percentage of sediments trapped upstream of the strips.

Fig. 2 shows how plant species and plant growth affected Manning's roughness coefficient. The presence of plants significantly increased the strip roughness. Results of ANOVA were similar to those obtained for total sediment retention. Only the interaction

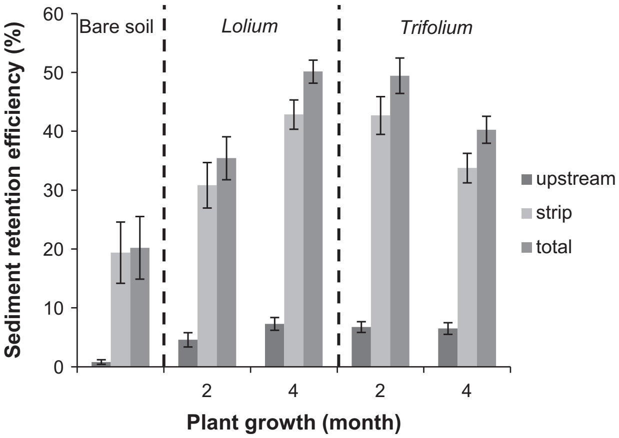

Fig. 5. Measured sediment retention (%) for different vegetative filter strips (*Trifolium repens*, *Lolium perenne* and bare soil as control) 2 or 4 months after plant germination. The total retention efficiency is the sum of the retention upstream of the strips and retention inside the strips. Values are means ($n = 8$), standard errors as error bars.

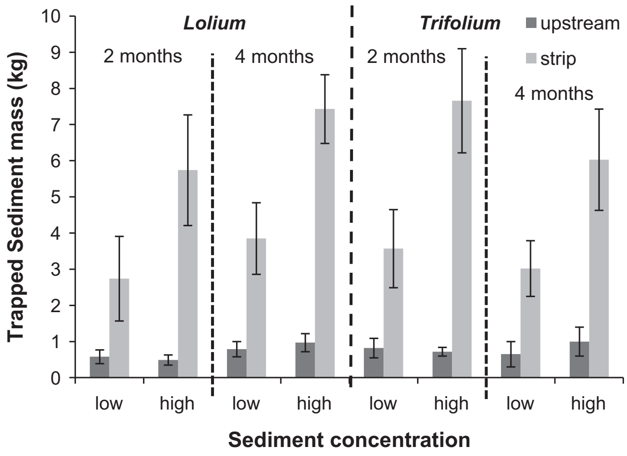

Fig. 6. Measured trapped sediment masses (kg) for different vegetative filter strips (*Trifolium repens*, *Lolium perenne* and bare soil as control) 2 or 4 months after plant germination for 2 different sediment concentrations (high 38.8 g l^{-1}, low 23.4 g l^{-1}). Sediments were trapped upstream of the strips ("upstream") and retention inside the strips ("strip"). Values are means ($n = 4$), standard errors as error bars.

plant species *x* plant growth stage was significant ($p = 0.0002$), reflecting the fact that Manning's coefficient increased significantly with plant growth duration for *L. perenne*, but remained unaffected for *T. repens*. Manning's coefficient was significantly correlated with total sediment retention (Pearson correlation coefficient $r = 0.62$). The Pearson correlation coefficients of some plant characteristics with Manning's coefficient were also calculated: plant density, tillering for *L. perenne* and number of leaves for *T. repens*. On average for both plant species, Manning's coefficient was mildly correlated to plant density ($r = 0.36$). But if only *L. perenne* was considered, highly significant correlations were detected with plant density ($r = 0.66$) and especially with grass tillering ($r = 0.87$). A decrease in plant density, along with an increase in heterogeneity inside the strips, was detected for *T. repens* after 4 months of growth in comparison to 2-month old strips (results not shown). These modifications may have resulted from plant senescence linked to intraspecific competition. Although for *T. repens* Manning's coefficient and plant density both decreased with growth duration, no significant correlation was detected between these 2 parameters, nor was there any correlation between Manning's coefficient and the number of leaves. The impact of grass tillering could also be statistically detected based on the vegetation spacing parameter (Fig. 3). Indeed, vegetation spacing significantly decreased with growth duration for *L. perenne* (growth effect: $p = 0.0002$; plant *x* growth interaction: $p = 0.0145$). *L. perenne* had also lower stem spacing than *T. repens* ($p < 0.0001$).

Sediment retention in the strips led to a modification of the particle size distribution at the outlet, in comparison to the incoming sediment (Fig. 7). There was a general decrease of the coarse silt fraction and especially of the sand fraction, as well as a slight increase of fine silt and clay fractions. These data are supplemented by Table 2, which indicates the VFS retention efficiencies of the different particle size fractions. These modifications of the particle size distribution were correlated with the total sediment retention, as shown by Pearson correlation coefficients between the different particle size fractions and total retention: sand ($r = -0.53$), coarse silt ($r = -0.56$), fine silt ($r = +0.55$), and clay (not significant). Some

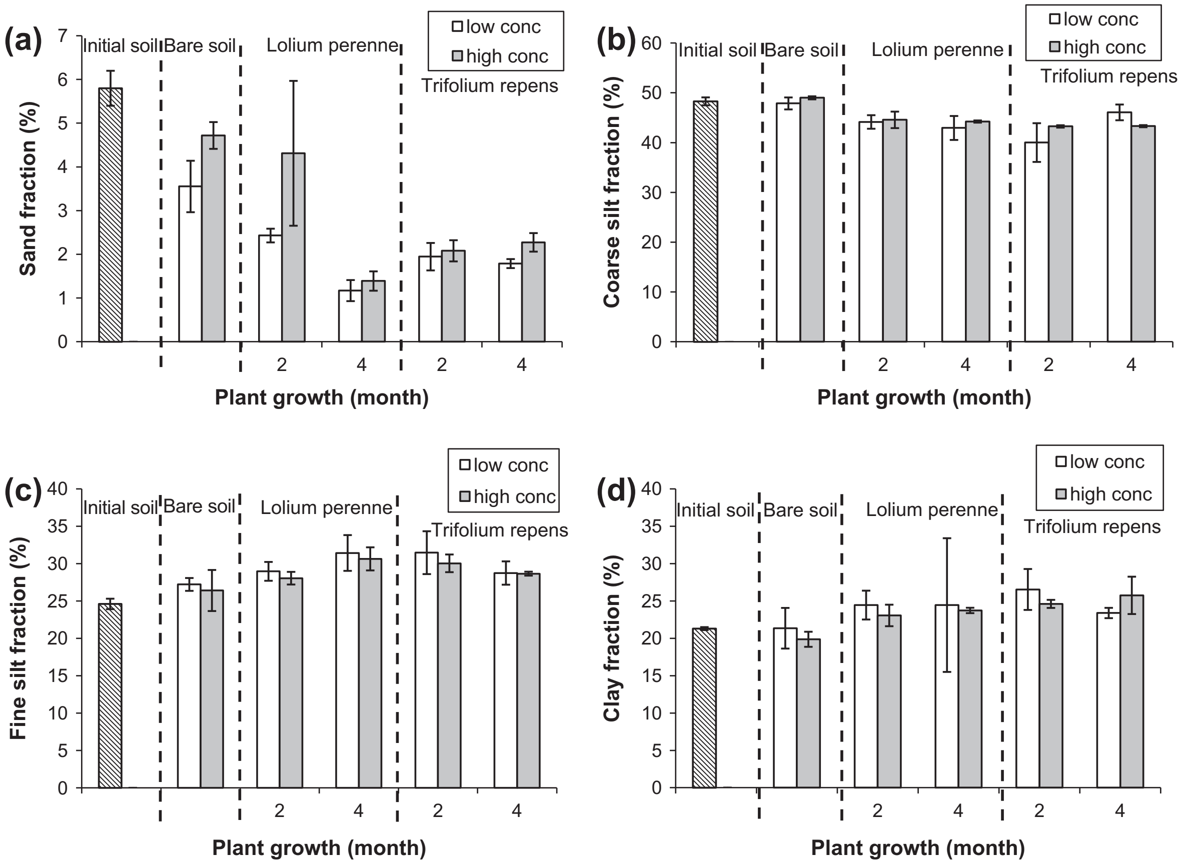

Fig. 7. Particle size fractions ((a) sand 2 mm < *d* < 50 μm; (b) coarse silt 50 μm < *d* < 20 μm, (c) fine silt 20 μm < *d* < 2 μm, (d) clay *d* < 2 μm) recorded at the outlet of the flume for 2 different sediment concentrations (38.8 and 23.4 g l^{-1}) and different vegetative filter strips (*Trifolium repens*, *Lolium perenne* and bare soil as control) 2 or 4 months after plant germination. These particle size distributions are compared to the incoming sediment (initial soil). Values are means ($n = 4$), standard errors as error bars.

Table 2
Retention efficiencies of the different particle size fractions (sand 2 mm $< d <$ 50 μm; coarse silt 50 μm $< d <$ 20 μm, fine silt 20 μm $< d <$ 2 μm, clay $d <$ 2 μm) for 2 different sediment concentrations (high 38.8 g l^{-1}; low 23.4 g l^{-1}) by different vegetative filter strips (*Trifolium repens*, *Lolium perenne* and bare soil as control) measured 2 or 4 months after plant germination. Values are means ($n = 4$), standard errors between brackets.

VFS	Growth (month)	Sediment conc.	Clay ret. (%)	Fine silt ret. (%)	Coarse silt ret. (%)	Sand ret. (%)
Trifolium	2	Low	37.8 (4.3)	36.3 (5.1)	56.9 (8.4)	82.2 (4.9)
		High	42.1 (5.5)	38.4 (7.1)	54.9 (4.8)	81.7 (3.6)
	4	Low	34.4 (4.3)	30.6 (1.0)	42.4 (5.6)	81.6 (1.9)
		High	28.0 (4.3)	30.5 (1.8)	46.5 (2.0)	76.9 (1.8)
Lolium	2	Low	26.6 (5.9)	24.2 (7.0)	41.3 (5.2)	73.1 (3.4)
		High	29.8 (5.1)	25.9 (4.9)	39.9 (4.2)	69.9 (5.7)
	4	Low	42.8 (13.6)	39.0 (2.9)	57.6 (1.0)	90.6 (1.7)
		High	45.9 (0.9)	39.3 (2.7)	55.4 (1.8)	88.4 (1.8)
Bare soil	/	Low	21.0 (4.4)	11.8 (6.6)	20.0 (9.5)	49.3 (12.3)
		High	26.3 (7.5)	16.3 (8.1)	18.2 (12.1)	36.7 (5.1)

significant treatment impacts were detected for the sand fraction but not for the other fractions (Fig. 7). Higher runoff sediment concentration led to higher sand fraction at the outlet of the strips ($p = 0.0258$). Moreover, the same plant species x plant growth stage interaction as for total sediment concentration and Manning's coefficient was detected ($p = 0.0292$).

3.2. VFSMOD results

After model calibration, predicted outgoing sediment masses matched well with experimental values, with Nash–Sutcliffe coefficients higher than 0.99 (Fig. 8). However, the calibration procedure modified the incoming sediment concentrations, and therefore the incoming sediment masses were not the same between the observations and the predictions. The corresponding observed and simulated mean retention efficiencies are shown in Fig. 9 in terms of modeling fitness. Consideration of experimental uncertainty for the incoming mass (error bars in Fig. 9; Eq. 7) resulted in acceptable modeling fitness ($C_{eff} = 0.76$; RMSE = 6.99%), higher ($C_{eff} = 0.86$; RMSE = 3.65%) if control strips were not considered. Fig. 10 compares the mean simulated and experimental sediment trapping efficiencies for the various treatments. VFSMOD tended to overestimate the retention efficiencies and could not predict well retention efficiencies for control strips without plant cover. Despite this bias, simulated retention efficiencies exhibited the same trends as for experimental results, i.e. an increase of sediment trapping efficiency of *L. perenne* with growth duration, and the opposite effect for *T. repens*.

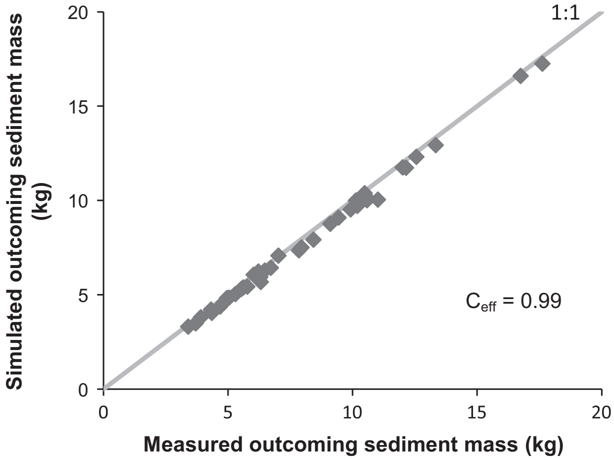

Fig. 8. Scatterplot of measured and simulated outgoing sediment masses (kg) after model calibration, with indication of Nash–Sutcliffe efficiency coefficients.

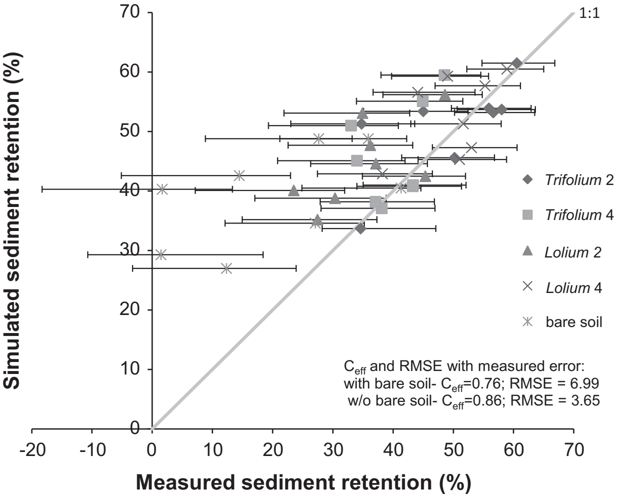

Fig. 9. Scatterplot of measured and simulated sediment retentions (%) of different vegetative filter strips (*Trifolium repens*, *Lolium perenne* and bare soil as control) 2 or 4 months after plant germination. Measurement uncertainty for each measured value plotted as an error bar, and Nash–Sutcliffe efficiency coefficients (C_{eff}) and root mean square errors (RMSE) are shown.

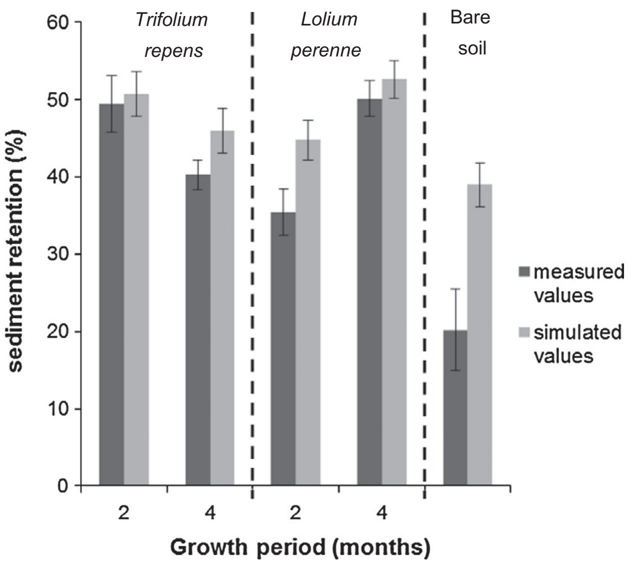

Fig. 10. Comparison of measured and simulated sediment retention efficiency (%) of different vegetative filter strips (*Trifolium repens*, *Lolium perenne* and bare soil as control) 2 or 4 months after plant germination. Values are means ($n = 4$), standard errors as error bars.

4. Discussion

We investigated the impact of plant growth and species as well as runoff sediment concentration on sediment retention using an experimental flume. The study is restricted to 1-m width, non-draining strips and with selected experimental conditions (slope, sediment concentration, water discharge). Regarding the strip width, USDA recommendations for buffer strip width is at least 6 m when used for sediment retention (USDA, 2000). However, VFS efficiency to trap sediments decreases exponentially with width and some authors showed that sediment trapping mechanisms were most effective in the five first meters of the VFS (Dillaha et al., 1989; Syversen, 2005; Gharabaghi et al., 2006). Moreover, Deletic and Fletcher (2006) measured the largest amount of trapped sediments in the first meter of their experimental device. Therefore, the 1 m width appears to be sufficient to investigate the dominant retention mechanisms of VFS. Secondly, the flume was designed so as to avoid infiltration. The majority of transported sediment in the field results from few extreme rainfall events in terms of intensity and/or duration, leading to high runoff flows (Liu et al., 2008). Under such circumstances, the main retention process is due not to soil infiltration, but to a greater resistance to surface flow by plant cover, leading to a decrease of the transport capacity and sedimentation of the excess soil particles (Dorioz et al., 2006; Fox et al., 2010; Ghadiri et al., 2001; Muñoz-Carpena et al., 1999).

The presence of plants significantly increased sediment trapping within the strips compared to bare soil (Fig. 5). However, the two selected plant species differed in terms of their ability to retain sediment, and how their retention efficiency changed with growth stage. The retention efficiency of *L. perenne* was around 35% after 2 months and increased to around 50% two months later, whereas the retention efficiency of *T. repens* was on average 49% after 2 months and showed a tendency to decrease after 4 months (around 40%). Morphological characteristics of shoots, such as tillering or number of leaves, in combination with plant density likely modified the strip's hydraulic roughness, as demonstrated by the significant Pearson correlation coefficients between Manning's coefficient and plant parameters. Indeed, each plant conformation will have a specific propensity to affect flow characteristics according to its shape (Erktan et al., 2013; Gumiere et al., 2011). As sediment retention efficiency was significantly correlated with the strip's roughness, the evolution of plant characteristics with growth stage necessarily influenced the strip's effectiveness to trap sediments. Owing to its shoot architecture (creeping stolons with big leaves), *T. repens* quickly developed an efficient barrier to water flow, leading to important sedimentation. However, changes in plant development between 2 and 4 months growth duration were small. A small decrease of plant density was observed visually after 4 months, possibly due to intraspecific competition and to the small soil thickness of the experimental VFS, which may explain the declining, yet not significantly different, sediment trapping efficiency (Fig. 5). On the other hand, the limited ability of *L. perenne* to trap sediments after 2 months may be explained by the architecture of the young shoots, as thin erect stems are less effective obstacles to runoff. Tadesse and Morgan (1996) have also shown with different plant species, *Festuca ovina* and *Poa pratensis*, that different shoot architectures led to contrasting trapping efficiencies. However, other authors demonstrated that grasses with erect growth habit of interwoven stems could be more effective to reduce erosion than plants with a more horizontal growth form (Morgan, 2005). Owing to the continuous grass development, and especially because of the increase in tillering (Fig. 3), sediment retention within the *L. perenne* strips rapidly exceeded that of *T. repens*, confirming literature. Plant phenological parameters are therefore essential components governing the capacity of strips to trap sediments. The tillering capacity was highlighted by several authors as a crucial plant parameter for setting up VFS (Xiao et al., 2011). Furthermore, in agreement with some authors like Otto et al. (2008), the present results underline that VFS are dynamic systems with no constant performance over time, especially during the early stages of plant development. This assertion should be understood in terms of changes of plant density as well as morphology. In terms of best management practices, this study suggests that, because the ability of grass species to trap sediments is low at the first stages of plant development, other plant species which present a more efficient trapping efficiency just after VFS establishment should be used, such as *T. repens*. The use of a mix of plant species for VFS includes of course other advantages, like self-fertilization with legume species, or an extended presence of shoots during the seasons. However, a high morphological diversity of the plant barrier may decrease the VFS potential to trap sediments, as shown by Erktan et al. (2013).

Sediment filtering by VFS modified the particle size distribution between the incoming and outgoing sediments (Fig. 7) (Syversen and Borch, 2005; Deletic and Fletcher, 2006; Gharabaghi et al., 2006). Smaller soil particles need lower energy levels and more time within the filter to settle (Liu et al., 2008), leading to an enrichment of fine soil particles at the outlet of the strips. The greater the increase in strip hydraulic roughness due to changes in plant parameters, the higher the sediment retention by VFS and the stronger the decrease in sand fraction at the outlet of the flume (Figs. 5 and 7). Many authors have shown that the retention of fine soil particles is not efficient in the first meters of the strips (Dorioz et al., 2006; Krutz et al., 2005; Muñoz-Carpena et al., 1999), thus leading to significant higher percentage of clays downstream of the VFS. However, clays can be associated to other soil particles to form stable aggregates of higher diameter. Syversen and Borch (2005) observed sedimentation of clays at the front of the strips, explained by a deposition of clays as aggregates. The retention efficiency of clays was surprisingly high in the present study, and increased with the increase in sediment trapping (Table 2 and Fig. 5). Moreover, retention efficiency of fine silts was more or less the same as for the clays. This suggests that the main part of the clay fraction was in fact trapped as aggregates.

Flow retardation by VFS starts a short distance upstream of the strips, leading to a decrease of transport capacity and sedimentation (Gumiere et al., 2011; Hussein et al., 2007; Neibling and Alberts, 1979). However, it appears that the mass of sediment that could be trapped upstream is limited (Fig. 6). Indeed, the mean sediment mass retained upstream of the VFS for the high incoming concentration (0.80 kg) was only slightly higher compared to the mass retained for the low concentration (0.71 kg). Therefore, the percentage of total sediments trapped upstream of the VFS decreased with increasing incoming sediment mass. Ghadiri et al. (2001) and Meyer et al. (1995) described a mechanism of sediment deposition, which was also observed during the experiments of the present study, whereby the rise of water level due to flow retardation by plants was called backwater. Deposition of coarse particles appeared first at the starting edge of the backwater to form a delta, which was established when flow first hit the strip. Deposition continued towards the strips until the delta reached the strip limit. The accumulation of sediments within the strips could increase flow retardation and raise the water level during the runoff event. This rising, together with sediment deposition, caused the initial backwater to move slowly upslope and sediments to deposit higher up (Rose et al., 2003). However, sediment deposition upstream of the VFS cannot increase endlessly and is limited by strip roughness (Pan et al., 2011). Moreover, bedload transport of the coarsest particles (Hussein et al., 2007) will gradually transfer deposited coarse particles and aggregates downstream to the wedge zone, causing a partial turn-over of these soil particles in the zone of upslope deposition. As sand particles are mainly trapped upstream and in the first meters of the strips, the sand trapping capacity of strips could also be limited, thereby explaining why the sand fraction collected at the outlet of the VFS increased with incoming sediment concentration. It was therefore demonstrated that sediment concentration had little effect on the mass but strongly affected the percentage of sediments trapped upstream of the strips, because of a maximum retention capacity. However, since upstream retention was low in comparison to sediment trapping within the strips (Fig. 5), incoming sediment concentration had no significant impact on total retention in the present study.

VFSMOD simulations concerning the impact of plant parameters on sediment retention were able to reproduce the same trends as observed during experiments (Fig. 10). Plant characteristics can be effectively introduced into VFSMOD through several parameters. First, Manning's roughness coefficient for the strips, which depends on soil surface conditions and plant cover. In VFSMOD, this parameter is used in the hydrology submodel (infiltration and overland flow), and not in the sediment transport submodel (Muñoz-Carpena et al., 1999). Muñoz-Carpena et al. (1993) showed that this parameter controls mainly the time to peak of the outgoing hydrograph. However, as the two submodels are linked together with feedback relations, Manning's strip coefficient affects flow velocity and volume and therefore indirectly sediment trapping efficiency. Global sensitivity analyses were performed for the vegetative filter strip hydrology and sedimentation modules by Muñoz-Carpena et al. (2010), based on three different experimental data sets (Arora et al., 1996; Pätzold et al., 2007; Poletika et al., 2009). Sediment trapping prediction was found to be relatively insensitive to Manning's coefficient, except for the data set of Arora et al. (1996). Regarding the plant parameters for the sediment filtration submodel, tillering was taken into account in VFSMOD, as it affects vegetation spacing. Muñoz-Carpena et al. (1999), (2010) demonstrated the sensitivity of sediment trapping prediction to this input factor. However, the same studies also revealed that sediment outflow was not sensitive to plant height, and only sensitive to the filter media modified Manning's coefficient under specific conditions, in case of concentrated flow (Fox et al., 2010) or low slopes (Arora et al., 1996). The latter parameter was impossible to assess from our experimental data, and was found to be unimportant for total sediment retention prediction (results not shown). Therefore, the impact of plant characteristics can be implemented into VFSMOD mainly through vegetation spacing without a significant loss of information.

The uncertainty inherent to the measured data used to calibrate the model was included into the model evaluation (Fig. 9). This kind of approach provides modelers with a simplified method to consider the crucial issue of uncertainty in model evaluation (Beven, 2006; Harmel and Smith, 2007; Reckhow, 1994). Although acceptable simulation results were obtained in general, goodness-of-fit indicators showed a bias between measured and simulated sediment retention efficiencies (Figs. 9 and 10). Goodness-of-fit indicators also show that prediction of sediment trapping with bare soils were overestimated (Figs. 9 and 10), as already reported by Abu-Zreig (2001).

Other sources of uncertainty inherent to parameter estimation can be highlighted. For strips with low plant cover development, it was observed that flow was not always distributed across the entire width of the VFS. This reduction of actual flow width could lead to a reduction of the trapping efficiency, and so to simulation overestimation since flow width was assumed to be equal to the strip width. In addition, previous work discussed modeling with VFSMOD the effects of flow concentration resulting from preferential flow paths through the filter (Fox et al., 2010). Abu-Zreig (2001) discussed the inclusion of longer, meandering flow paths sometimes found in natural filters, by modifying the effective value of the parameter "strip width" (Table 1). When heterogeneous vegetation is present in the filter, it is possible to parametrize in VFSMOD the surface segments with different values along the flow path (roughness, slope). Another source of uncertainty is linked to the calculation of Manning's coefficients for the bare soil and for the VFS, which were higher than other ones published in the literature. For example, Engman (1986) indicated values of 0.01–0.033 for bare soil, and 0.10–0.63 for grass prairie. Capillary rise on the dye coated plates may have led to an overestimation of the measured water height in the strips. An estimation of the impact of capillarity on water height assessment was made subsequent to the experiments. Values of water height may be overestimated by up to 2 mm, and this overestimation could lead to underestimation of runoff velocity, based on Eq. (1), up to 20%. Although it was impossible to quantify this overestimation *a posteriori* for each run, Manning's values determined in the present study were consistent with other studies involving flows that are shallower than the vegetation roughness elements (Huggins and Burney, 1982; Loch et al., 2009).

5. Conclusions

The use of an experimental flume allowed to investigate the impact of plant morphology and growth of *L. perenne* and *T. repens* on sediment retention efficiency of VFS, as well as the impact of incoming sediment concentration. This kind of flumes offers also other investigation possibilities, such as the potential reduction of the VFS trapping efficiency under the effects of successive runoff events, or the potential of root architecture to reduce the runoff volume through improved soil permeability (as performed for example for soil detachment rate by De Baets et al. (2007)). The capacity of VFS to trap sediments upslope of the strips was limited in terms of mass, and therefore an increase in sediment concentration led to a decrease in sediment retention efficiency. However, sediment trapping upstream of the strips was low in comparison to retention within the strips, and sediment concentration did not affect the total retention efficiency. After 2 months of plant growth, plant morphology significantly affected the VFS potential to trap sediments, as observed with the higher efficiency of *T. repens* due to its creeping shoot architecture. However, continued plant growth and development modified the plant morphology and the VFS trapping potential. The crucial importance of tillering capacity of grass species such as *L. perenne* that increases sediment retention capacity was thus highlighted. The strong variation of the VFS trapping efficiency with plant development should be taken into account into best management practices for limiting soil erosion. The modification of plant parameters with growth stage can be integrated into a mechanistic model such as VFSMOD mainly through stem spacing. Indeed, an increase in tillering for grass species reduced the stem spacing values and led to higher sediment trapping. Strip surface roughness, assessed by Manning's coefficient, was also correlated to plant morphology and affected the prediction of flow retardation by strips and therefore trapping potential. As these parameters were highly conditioned by plant growth and development, modelers should take into account plant growth dynamics and select plant parameters that reflect the actual field conditions.

Acknowledgements

The authors would like to thank Guido Rentmeesters for his great technical help concerning the conception of the experimental flume, and Anne Iserentant for her technical assistance for the soil analysis. Thomas Lambrechts thanks the "Communauté Française de Belgique" for the research internship grant at the Agricultural and Biological Engineering Department of the University of Florida. Rafael Muñoz-Carpena acknowledges the support from University of Florida Foundation Professorship.

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